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Forest Research Report No. 164

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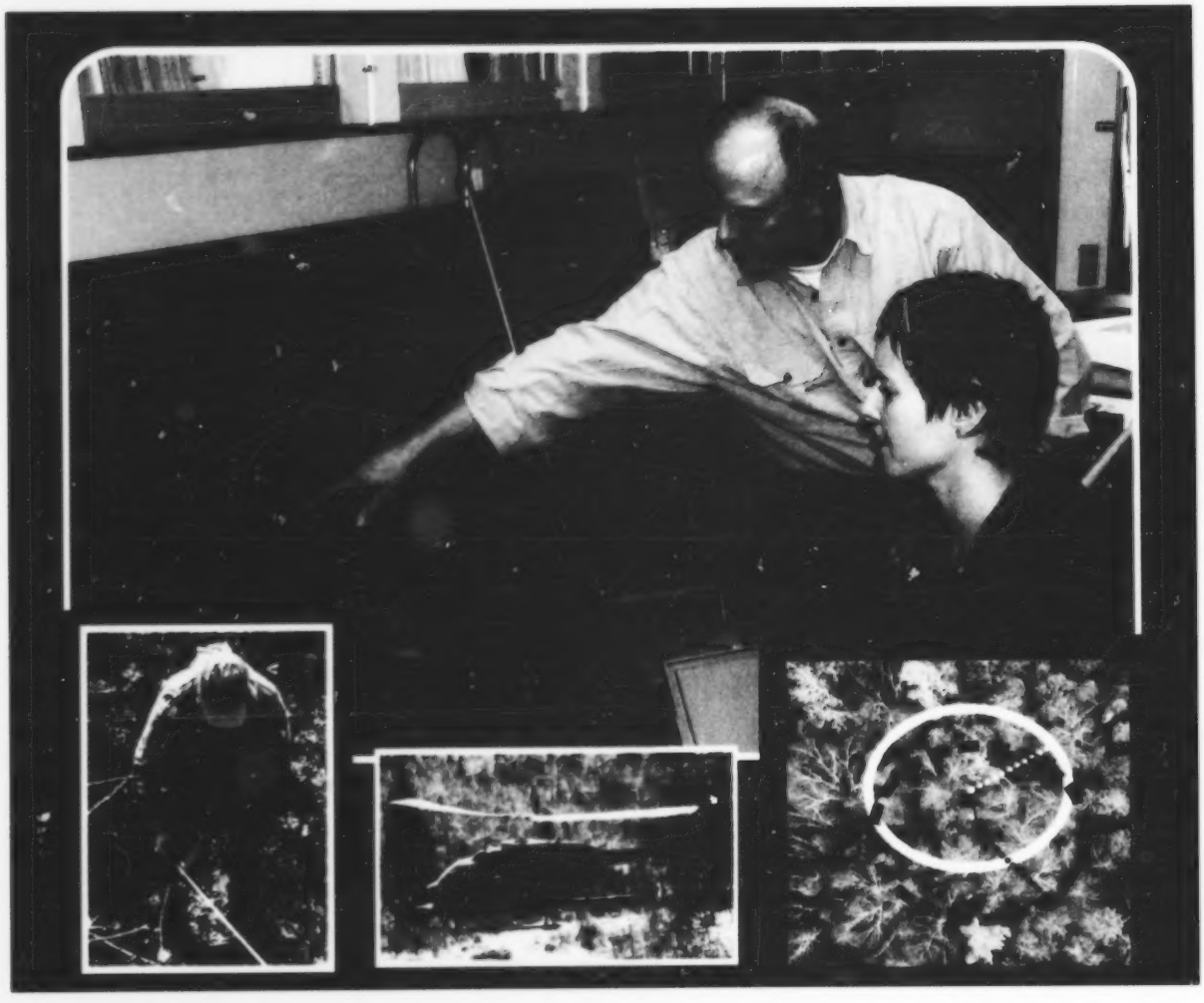

Ontario Forest Research Institute

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## *in mixed and hardwood forests of the Great Lakes-St. Lawrence region of Ontario*

by

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## Abstract

Large-scale photography (LSP, >1:1000) may be a useful tool to measure traditional and non-traditional forest attributes. LSP has worked well for plot-level sampling in boreal Canada, but has not been rigorously tested in mixed and hardwood forests, such as those of the Great Lakes-St. Lawrence region of Ontario, where forests have greater species diversity and often more vertical structure. We evaluated an LSP system for plot sampling in Great Lakes-St. Lawrence forests by comparing the utility of leaf-off and leaf-on imagery (1:433), assessing targeting accuracy, and comparing ground and LSP values for some commonly measured inventory, research and monitoring variables (e.g., species identification, tree height, DBH), and for less commonly measured variables (e.g., canopy closure, hardwood tree quality, and snag and downed wood size and decay class).

Spring, leaf-off imagery that captures phenological differences among species is optimal for identifying tree species, and detecting and measuring plot variables in Great Lakes-St. Lawrence forests. In leaf-on images, foliage interfered with altitude measurement and thus photo scale determination, and obscured feature detection and measurement. We therefore used only leaf-off imagery to assess targeting accuracy and to compare ground and photo measurements.

The targeting accuracy of the system, which averaged 8.7 m, is likely sufficient for temporary sample plots used in most operational forest inventories, but may not be adequate for sampling or re-sampling permanent research or monitoring plots, depending on plot size. Likewise, LSP measurements of a variety of features may be adequate for plots used for forest inventory purposes, but likely are not accurate or precise enough for repeated sampling of permanent plots. Differences between ground and LSP measurements tended to be smaller for conifers than for hardwoods (with the exception of poplars). These differences are quantified to help practitioners determine the suitability of LSP for their applications.



## Résumé

Mise à l'essai de la photographie à grande échelle pour caractériser des parcelles d'échantillonnage à des fins d'inventaire forestier dans des forêts mixtes et de feuillus de la région ontarienne des Grands Lacs et du Saint-Laurent

La photographie à grande échelle (échelle supérieure à 1:1 000) peut être un bon outil pour mesurer des caractéristiques forestières conventionnelles et non conventionnelles. Elle s'est avérée appropriée pour caractériser des parcelles d'échantillonnage de la forêt boréale du Canada, mais n'a pas été mise à l'épreuve de façon rigoureuse dans des forêts mixtes et de feuillus, telles celles de la région ontarienne des Grands Lacs et du Saint-Laurent, qui présentent une plus grande diversité d'espèces et souvent une structure plus verticale. Nous avons évalué un système de photographie à grande échelle pour caractériser des parcelles d'échantillonnage dans des forêts de la région des Grands Lacs et du Saint-Laurent, en comparant l'utilité des images de peuplements avec et sans feuilles (1:433), en évaluant l'exactitude du ciblage et en comparant les valeurs au niveau du sol avec celles de la photographie à grande échelle pour des variables en fait d'inventaire, de recherche et de surveillance (p. ex., identification des espèces, hauteur des arbres et diamètre à hauteur de poitrine) qui sont couramment mesurées, et pour des variables moins couramment mesurées (p. ex., fermeture du couvert forestier, qualité des feuillus, taille des chicots et des arbres abattus ou déracinés, et classe ou catégorie de désintégration). Les images d'arbres sans feuilles (au printemps), qui permettent d'enregistrer les différences phénologiques entre les espèces, sont parfaites pour identifier les espèces d'arbres et détecter et mesurer les variables liées aux parcelles dans des forêts de la région des Grands Lacs et du Saint-Laurent. Lors de l'utilisation des images d'arbres portant des feuilles, le feuillage interférait avec les mesures d'altitude et donc avec la détermination de l'échelle des photographies, ce qui rendait difficiles la détection et la mesure des diverses caractéristiques. Par conséquent, nous n'avons utilisé les images d'arbres sans feuilles que pour évaluer l'exactitude du ciblage et comparer les mesures au sol avec celles des photographies. L'exactitude du ciblage, situé en moyenne à 8,7 m, est probablement suffisante pour les parcelles d'échantillonnage utilisées dans la plupart des inventaires forestiers, mais pourrait, selon la superficie des parcelles, ne pas être appropriée pour l'échantillonnage répété des parcelles permanentes. De même, les mesures de toutes sortes de caractéristiques qui sont obtenues par la photographie à grande échelle peuvent être appropriées pour les parcelles d'échantillonnage utilisées pour les inventaires forestiers, mais ne sont probablement pas suffisamment précises pour l'échantillonnage répété des parcelles permanentes. Les différences entre les mesures au sol et celles obtenues par photographie à grande échelle tendent à être moins importantes pour les conifères que pour les feuillus (à l'exception du peuplier). Ces différences sont quantifiées pour aider les professionnels à voir si la photographie à grande échelle convient à leurs travaux.

## Acknowledgements

Living Legacy Trust provided funding for this project through the Upper Lakes Environmental Research Network (Project 08-039). Additional funding was provided by Ontario Ministry of Natural Resources through the Ontario Terrestrial Assessment Program and the Forest Health and Silviculture Section. Large-scale photography was taken by WiskAir (Thunder Bay, ON). RMAP™-based interpretations were by R&B Cormier (Sault Ste. Marie, ON). Jorma Paloniemi and Adam Rudzki provided supplementary LSP interpretations. We also thank our field crews for their data collection efforts. Doug Pitt, Lisa Venier, Rob Cormier, and Lisa Buse provided helpful reviews of an earlier version of this manuscript. Graphics and layout support for this report were provided by Trudy Vaittinen.

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## Introduction

Forest resource inventories are central to sound forest management as they provide the basis for describing the current forest, planning management activities, and forecasting future conditions. Inventory data have traditionally been interpreted from monochromatic, medium-scale photographs (MSP; usually at 1:10,000, 1:15,840, or 1:20,000 scales), with ancillary field plot sampling. As forest management becomes more ecosystem-focused, the need for more accurate data on more variables than can be derived from conventional MSP is increasing. Legislation such as Ontario's *Crown Forest Sustainability* (RSO 1994 c.25) and *Environmental Assessment Acts* (RSO 1990 c. E.18), forest certification standards (CAN/CSA-Z809-02, *Sustainable Forest Management: Requirements and Guidance*) and resulting market pressures, mean that forest companies increasingly require efficient, cost-effective methods to collect data on timber and non-timber values.

Since the 1960s, researchers have explored the use of large-scale photography (LSP, >1:1000 scale) to sample plots to augment forest inventory data from MSP (Lyons 1967; Aldred and Hall 1975). In addition to inventory, LSP has been used to assess regeneration (Hall 1984; Hall and Aldred 1992), evaluate vegetation management treatments (Pitt and Glover 1996; Pitt *et al.* 1997, 2000), estimate tree volumes (Aldred and Kippen 1967), and classify and map forest ecosystems (Sandmann and Lertzman 2003). These projects have shown that LSP can provide objective, quantitative, and cost-effective data for a variety of forest attributes.

Despite its demonstrated utility, LSP has not been widely adopted as a forest plot sampling tool in Ontario. Photo scale and measurement uncertainties (Aldred and Sayn-Wittgenstein 1972; Spencer and Hall 1988), targeting inaccuracies (Aldred and Hall 1975; Hall 1984), and inefficiencies of manual photogrammetry, have all limited its use.

Advances in LSP and supporting technologies (e.g., LiDAR, GPS), ranging from improvements in accuracies of photo scale, measurements (Kovats 1997), and targeting (Herwitz *et al.* 1998, 2000; Pitt *et al.* 2000), to development of software that automates some aspects of photogrammetry, are increasing the viability of LSP. The utility of LSP technology continues to grow as information demands, costs of field data collection, and concerns for worker safety escalate. Additional advantages of LSP are that less accessible areas can be surveyed and permanent records are available for data verification or re-measurement.

Previous tests of LSP plot sampling for forest inventory in Canada have focused on conifer forests (Lyons 1967) or conifer components of mixed forests (Aldred and Hall 1975). Mixed and hardwood forests, such as those of the Great Lakes-St. Lawrence region of Ontario, are not well represented in these studies. However, these forests present a rigorous testing ground for the application of LSP to interpretation of forest sample plot variables. Great Lakes-St. Lawrence forests often have high tree species diversity, with many species that are difficult to distinguish in aerial photos (Sayn-Wittgenstein 1960). These forests are typically uneven-aged, with much structural complexity that necessitates collecting data from multiple canopy layers. In contrast to boreal conifer forests, individual hardwood trees in this region can vary significantly in commercial value depending on their quality or grade. In Ontario, hardwood tree quality is not estimated from medium-scale photos as part of standard forest inventory practices, but is often evaluated as part of a pre-harvest stand cruise. The ability to accurately estimate individual tree or average stand quality from LSPs would significantly benefit silvicultural planning.

The objective of this study was to evaluate an integrated LSP acquisition and interpretation software system (RMAP™, R&B Cormier, Sault Ste. Marie, ON) for plot sampling in mature mixed and hardwood forests of the Great Lakes-St. Lawrence region. To do so, we compared the utility of leaf-off and leaf-on imagery, assessed the targeting accuracy of the LSP system, and compared ground-measured and LSP values for a variety of traditional and non-traditional forest plot variables.

## Methods

### Study area

We aerially photographed and field-sampled 104 plots; 95 of these were in the Algoma Forest of north central Ontario, within approximately 100 km of Sault Ste. Marie, and nine were on Cockburn Island, in the north channel of Lake Huron, about 110 km southeast of Sault Ste. Marie (Figure 1). These sites are within the Great Lakes-St. Lawrence forest region (Rowe 1972), near the western limits of Site Regions 4E and 5E (Hills 1959). Plot locations were selected to cover a range of the region's forest conditions, while limiting the total area of the study to minimize helicopter ferrying and data capture costs.

Ontario's Great Lakes-St. Lawrence forests are dominated by tolerant and mid-tolerant hardwoods, with intolerant hardwood and conifer associates. The most common deciduous species on sample plots are sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britton), white birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and trembling aspen (*Populus tremuloides* Michx.). The most common conifers are balsam fir (*Abies balsamea* (L.) Mill.), eastern white cedar (*Thuja occidentalis* L.), and eastern white pine (*Pinus strobus* L.).

Of the 95 Algoma plots, 81 were previously established permanent plots from research and monitoring projects (i.e., Ontario Ministry of Natural Resources (OMNR) Growth and Yield and Forest Ecosystem Classification (FEC) Programs, and a Canadian Forest Service hardwood silviculture research study, Stokely Creek). Fourteen new temporary plots were located in old-growth forests of the Algoma Headwaters Provincial Park, roughly 80 km northeast of Sault Ste. Marie. We anticipated greater structural complexity in these old-growth plots, including larger numbers of snags and fallen logs, than in the 81 second-growth plots. We sampled nine temporary plots on Cockburn Island, where phenology and composition differed slightly from Algoma.

### Acquiring large-scale photography

To compare the usefulness of leaf-off and leaf-on imagery in Great Lakes-St. Lawrence forests, we photographed plots in May (leaf-off) and July 2003

***Figure 1.*** *Map of Ontario with inset showing Algoma and Cockburn Island sample areas.*

(leaf-on). Simultaneous stereo pairs of LSPs were taken from a Bell 206 Long Ranger helicopter with a camera boom attachment (Figure 2). Front and rear Hasselblad MK70 cameras were mounted 6.1 m apart (Hall [1984] and Spencer and Hall [1988] provide good overviews of LSP systems generally, and Pitt *et al.* [2000] provide information about the tested system). The camera lenses were 100 mm focal length and had fiduciary plates that marked principal points on the film. We used Kodak Professional Portra 160, 70 mm, double-perforated, natural colour film. A pulse LiDAR altimeter measured height above the ground.

Prior to photography we determined plot centre coordinates for the 81 permanent plots using a global positioning system (GPS) in the field. We placed at least two ground targets in canopy openings on each plot to enable triangulation of plot centres on photos. For the 23 temporary plots, we determined plot centre coordinates from available maps.

The flight crew used a differential GPS navigation system (SoftNav®, Filanda Inc., St-Raymond, QC) to plan and fly LSP missions, with plot centre coordinates as targets. To optimize photo area, image resolution, and depth of field, we intended a flying altitude of 100 m, or approximately 80 m above the canopy. When the aircraft was within 5 m (horizontal distance) of plot centre (i.e., the target bubble), the cameras were enabled, and then triggered automatically and

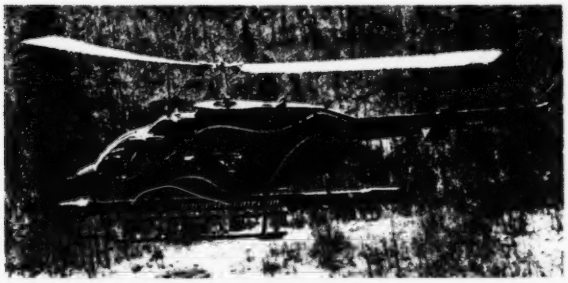


***Figure 2.*** *WiskAir Bell Long Ranger helicopter shown with LSP camera boom attached to the aircraft belly between the landing skids. GPS antenna is visible as small white shaft on cabin roof approximately 1 m forward of rotor. (Photo courtesy of WiskAir, Thunder Bay, Ontario)*

simultaneously when the helicopter's distance to target began to increase. Software (SoftNav®) recorded the time, and the aircraft heading (i.e, orientation), altitude, and ground speed at photo capture.

The film contact scale was 1:1000, covering a ground area of approximately 55 x 55 m. Altitude at photo capture, and thus photo scale, differed slightly among plots, and photo scale was calculated independently for each plot. We used print enlargements of 12.7 x 12.7 cm (approximately 1:430) for most interpretations, but also used enlargements of 20.3 x 20.3 cm (approximately 1:270) of the 14 old-growth plots for supplementary snag and downed wood interpretations.

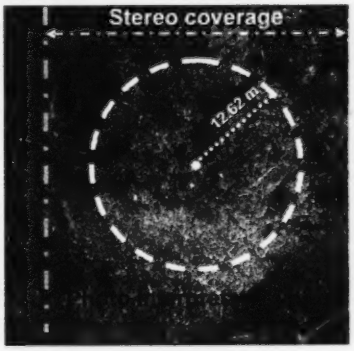
## Measuring variables from photographs

### *Training interpreters to identify Great Lakes-St. Lawrence species*

The photo interpreter had previously identified boreal tree species on large-scale photos, but required additional training to identify Great Lakes-St. Lawrence species. To do so, he visited non-study stands in the Algoma region and on Cockburn Island with additional LSPs taken during the May flight. Some uncommon species, such as ironwood (*Ostrya virginiana* (Mill.) K. Koch) and black cherry (*Prunus serotina* Ehrh.), occurred within sample plots, but did not occur in the training plots.

### RMAP™

RMAP™ software (adapted from software developed by Pitt [1994]) provides semi-automated interpretation and data management support for LSP. To use RMAP™, an interpreter positions a stereo LSP pair on a digitizing tablet, and uploads the flight mission data for the plot, including image reference numbers, heading, and altitude; RMAP™ calculates photo scale using altitude. The interpreter specifies a plot size (500 m² circular with origin at the rear principal point), and using a magnifying stereoscope and a digitizing pen, identifies features on the photos. RMAP™ determines if features are within the plot, and does not permit delineation of features outside the plot boundary. For trees, the crown centre, corrected for relief displacement, determines inclusion.



The interpreter determines tree species and, while viewing the tree in stereo, traces a radius from the tree centre to the crown edge, and then around the crown perimeter. Using a parallax bar, the interpreter measures tree height. From these measurements, RMAP™ calculates crown area, and from this area, crown diameter. Using species- and location-specific regression equations, RMAP™ calculates stem diameter at breast height (DBH, 1.3 m) for each tree based on its photo-measured height and crown diameter from the input regression equations. After the interpreter delineates and measures all trees, RMAP™ calculates canopy closure as the percentage of plot area occupied by tree crowns and species composition based on basal areas computed from stem diameters.

If requested by the client, the interpreter can also delineate snags and downed wood. For snags, the interpreter determines form class (poplar, other hardwood, pine, or other conifer) and measures height. RMAP™ calculates lengths of downed wood pieces.

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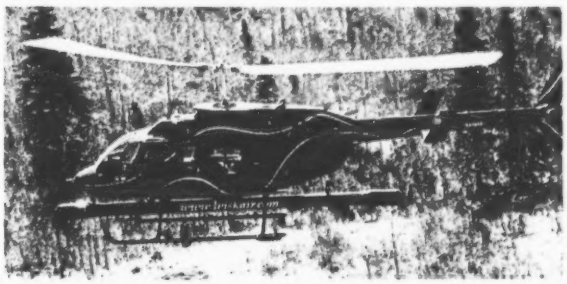

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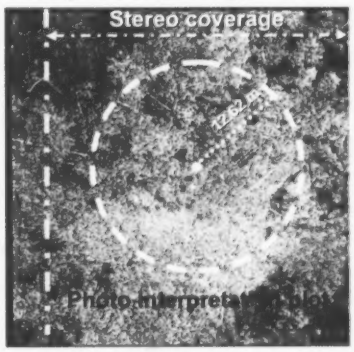


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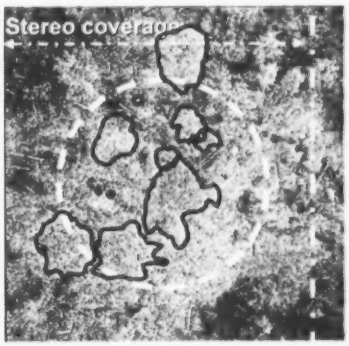


If requested by the client, the interpreter can also delineate snags and downed wood. For snags, the interpreter determines form class (poplar, other hardwood, pine, or other conifer) and measures height. RMAP™ calculates lengths of downed wood pieces.

### *RMAP™-based interpretation and measurement*

RMAP™ (see sidebar) was used to measure plot canopy closure and species composition (and then ecosite), tree and snag heights, tree crown and stem diameters, and downed wood lengths. Not all attributes were measured on every plot (Table 1). For the 81 permanent sample plots, the 500 $m^2$ photo plots did not overlap the ground plots exactly due to various target errors (discussed below), and the interpreter evaluated only the area of overlap (Figure 3). For the 23 temporary plots, the ground plots were established at the photo plot centre, and the entire 500 $m^2$ photo plot was interpreted.

The species-specific regression equations used to relate crown diameter and height to stem diameter for this study were developed by SpatialWorks (Sault Ste. Marie, ON), based on field measurements of tree height, crown diameter, and stem diameter collected for 11 species in Algoma and 10 species on Cockburn Island (Table 2). Sampled trees represented a range of diameters and were not located on study plots. Equations were estimated separately for Algoma and Cockburn Island data sets due to possible site and thus allometric differences.

***Table 1.*** *Summary of numbers of plots with variables measured.*

| | Pre-existing, permanent sample plots (PSPs) | | | | Temporary plot | |
|---|---|---|---|---|---|---|
| Variable | Stokely Creek (27)[a] | Growth & Yield (36)[a] | FEC (9)[a] | Shore Ridges Cons. Area (9)[a] | Old-growth (14)[a] | Cockburn Island (9) |
| **Plot variables[b]** | | | | | | |
| Targeting accuracy | 27 | 36 | | | | |
| Slope | 27 | 36 | | | | |
| Aspect | 27 | 36 | | | | |
| Canopy closure[c] | | 16 | | | | |
| Ecosite | | 36 | 7 | | | |
| Detection of trees | | | | | | 9 |
| Detection of snags | | | | | 14 | 9 |
| Detection of downed wood | | | 3 | | 14 | |
| **Tree/snag/downed wood variables[d]** | | | | | | |
| Tree species and form class | 27 | 36 | 9 | 8 | | 9 |
| Tree height[c] | 27 | 36 | 9 | 8 | | |
| Tree base of live crown (BLC) and live crown ratio (LCR) | | 36 | | | | |
| Tree crown diameter[c] | 27 | 36 | 9 | 8 | | |
| Tree DBH[c] | 27 | 36 | 9 | 8 | | 9 |
| Tree quality (hardwoods) | | 36 | | | | |
| Snag form class | 27 | 36 | 9 | 8 | 14 | 9 |
| Snag height[c] | 27 | 36 | 9 | 8 | 14 | 9 |
| Snag decay class | | | | | 14 | |
| Downed wood length[c] | | | 3 | | 14 | |
| Downed wood diameters (butt and top) | | | | | 14 | |
| Downed wood decay class | | | | | 14 | |

[a] Algoma region plots
[b] Entire 500$m^2$ LSP plot evaluated in the field
[c] RMAP™ variable
[d] For co-registered features on plots

### *Supplemental interpretation and measurement*

In addition to assessing standard RMAP™ attributes, interpreters measured targeting accuracy, plot slope and aspect, tree height to base of live crown (BLC, used to calculate live crown ratio, LCR), tree quality, snag form class, snag and downed wood decay classes, and downed wood diameter (Table 1).

To evaluate targeting accuracy, we measured photo distances between the ground plot centre (of 81 permanent plots) and each of the front and rear principal points, and the stereo image centre using digital calipers (Figure 3). To measure slope and aspect, the interpreter used a magnifying stereoscope. If the plot was on a slope, the interpreter measured slope percent by comparing ground heights 5 m either side of photo plot centre, along the direction of the slope. For these plots, he determined aspect from the photo heading using a Douglas protractor.

The interpreter used a parallax bar to measure tree height and BLC for trees where ground and photo plots overlapped. From BLC, we computed LCR as the proportion of the tree's height with live crown.

Using as much of the stem as visible, the interpreter classified tree quality of tolerant and mid-tolerant hardwoods using the six-class central Ontario hardwood tree quality classification system (OMNR 2004, Table 3.15). We subsequently combined these into two classes, acceptable growing stock (AGS) and unacceptable growing stock (UGS) (OMNR 2004). Acceptable growing stock are trees of better quality and vigour, projected to persist and maintain or improve in quality by the next stand entry. Unacceptable growing stock are trees of high risk or poor form, projected to decline or not to improve in quality by the next stand entry.

Using the 20.3 x 20.3 cm photos for the 14 old-growth plots, the interpreter determined decay class for each snag and log using a 3-class system modified from a 5-class system used in British Columbia (BC. Min. Environ. Lands Parks/BC. Min. For. 1998):

Class 1 = recently dead, bark mostly on, most branches still attached, most of tree height intact;

Class 2 = partly decomposed, branches and bark off (bare logs, stubs), tree height 50-75% of original;

Class 3 = decomposition evident, moss encroaching on log and various levels of incorporation of material into forest floor, standing material reduced to broken stubs, stumps and hollow, <50% of original height.

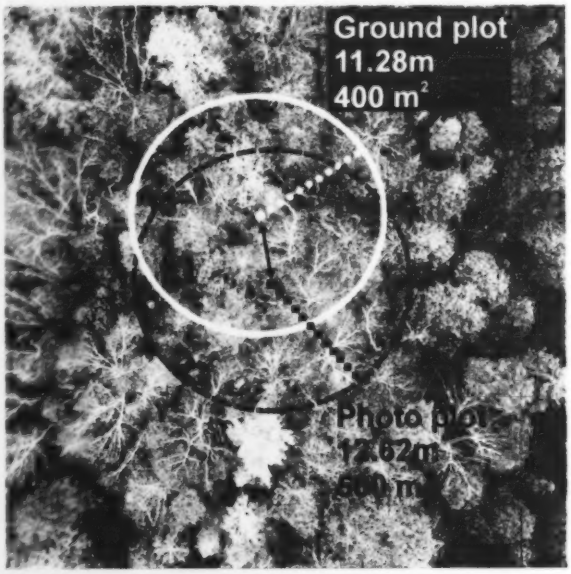


***Figure 3.*** *Diagram showing 400 m² ground sample plot and standard 500 m² LSP interpretation plot. The photo mission goal was to achieve the smallest possible distance between photo and ground plot centres. Mean total distance for 81 ground plots was 8.7 m, with a standard deviation of 4.2 m, resulting in a mean of 61% area overlap between plot types.*

The interpreter then measured downed wood diameter at each log end using a fine-tipped pen nib as a measuring scale (pen nib was 0.35 cm diameter, or approximately 9.5 cm at 1:271 scale).

## Collecting field data

We collected ground data on 103 sample plots; 80 of 81 permanent plots (one FEC plot was excluded because only 3% of the ground plot was captured within the LSP plot) and 23 temporary plots (Table 1). From the permanent plots, we sampled across a range of tree species and sizes to test LSP's effectiveness for measuring various tree attributes. We assessed detection rates of trees, snags, and downed wood over the entire 500 m² LSP plot on a subset of plots.

Field crews used hand-held GPS units to navigate to each plot, and then used prominent features on LSPs (e.g., distinctive trees, rock outcrops, downed wood) to locate and mark the photo centre. Crews flagged the perimeter of the 500 m² (circular, radius = 12.62 m) LSP plot on the ground. For permanent plots, they measured

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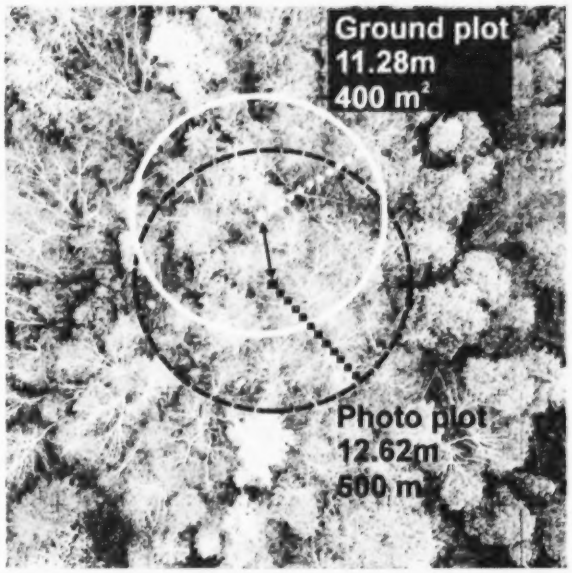


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***Table 2.*** *Model fit ($R^2$ and RMSE[a]) and descriptive statistics by species and location for individual sample trees used to develop tree crown-DBH regression models.[b]*

| Species | Location | n | $R^2$ | RMSE | Minimum DBH (cm) | Maximum DBH (cm) | Mean DBH (St. Dev.) |
|---|---|---|---|---|---|---|---|
| Poplar spp. | Algoma | 34 | 0.93 | 3.4611 | 3.8 | 55.4 | 22.0 (12.8) |
| | Cockburn Is. | 57 | 0.88 | 4.6782 | 2.5 | 48.4 | 22.3 (13.0) |
| Sugar maple | Algoma | 34 | 0.95 | 3.2981 | 2.6 | 54.3 | 21.4 (14.0) |
| | Cockburn Is. | 60 | 0.88 | 4.7114 | 2.5 | 53.4 | 24.0 (13.9) |
| Red maple | Algoma | 33 | 0.85 | 5.0055 | 3.9 | 53.7 | 22.6 (12.5) |
| | Cockburn Is. | 27 | 0.83 | 4.0322 | 2.0 | 33.4 | 14.5 (9.5) |
| Yellow birch | Algoma | 43 | 0.85 | 6.1597 | 2.9 | 60.5 | 25.1 (15.8) |
| | Cockburn Is. | 48 | 0.77 | 6.1270 | 2.9 | 47.2 | 21.4 (13.0) |
| White birch | Algoma | 22 | 0.86 | 4.7906 | 3.1 | 44.4 | 20.7 (12.1) |
| | Cockburn Is. | 21 | 0.90 | 4.6564 | 3.1 | 48.1 | 22.8 (14.0) |
| Northern red oak | Algoma | 42 | 0.94 | 3.4993 | 2.3 | 52.2 | 26.1 (14.8) |
| | Cockburn Is. | 48 | 0.88 | 4.7097 | 3.1 | 49.9 | 26.1 (13.2) |
| American beech | Cockburn Is. | 53 | 0.74 | 7.3613 | 3.5 | 63.5 | 24.8 (14.6) |
| White pine | Algoma | 19 | 0.93 | 5.1342 | 3.5 | 70.1 | 37.5 (18.5) |
| Red pine | Algoma | 9 | 0.90 | 4.3025 | 12.0 | 47.2 | 31.7 (11.7) |
| Balsam fir | Algoma | 32 | 0.94 | 2.5543 | 2.4 | 36.6 | 17.0 (9.9) |
| | Cockburn Is. | 24 | 0.92 | 1.5943 | 2.7 | 22.0 | 11.5 (5.9) |
| White spruce | Algoma | 34 | 0.95 | 3.3306 | 1.4 | 55.2 | 27.3 (15.1) |
| | Cockburn Is. | 36 | 0.91 | 3.0625 | 2.1 | 38.2 | 18.9 (10.0) |
| Eastern white cedar | Algoma | 35 | 0.95 | 2.3533 | 3.2 | 47.3 | 20.0 (11.7) |
| | Cockburn Is. | 46 | 0.89 | 3.85 | 2.9 | 44.8 | 19.4 (11.5) |

[a] Root mean squared error

[b] Models were estimated by SpatialWorks (Sault Ste. Marie, ON) using multiple linear regression and with tree crown diameter and tree height as independent variables. Model forms and parameter estimates are property of R&B Cormier.

plot variables (slope, aspect, canopy closure) over the entire LSP plot, but collected tree, snag, and downed wood data only within the overlap area of the LSP and ground plots (Figure 3). Permanent ground plots were usually 400 $m^2$ (circular, radius = 11.28 m) and boundaries were obvious from permanent markings. For temporary plots, the ground centre was established at the photo centre, and the entire LSP plot was sampled for plot and individual tree, snag, and downed wood variables.

### *Measuring plot-level variables*

Field crews measured slope and aspect on each plot using clinometer and compass, respectively, and visually estimated canopy closure (Hayden *et al.* 1995). Of the permanent plots, 43 had previously been classified to ecosite (Chambers *et al.* 1997). These data were extracted from OMNR databases for this study (K. Zhou, OMNR, Sault Ste. Marie, ON, pers. comm.).

### *Detecting and measuring trees, snags, and downed wood*

To evaluate the interpreter's detection errors for trees (≥ 2.5 cm DBH), snags (≥ 10 cm DBH), and downed wood (≥ 10 cm diameter) from LSPs, we co-registered interpreted data in the field, and tallied all detected and omitted features (Table 1). For trees and snags, we based our comparisons on the entire 500 $m^2$ photo plot. For

downed wood, we tallied all pieces that intersected at least one of two 20 m orthogonal transects through plot centre on the 14 old-growth plots, and all pieces on three 500 $m^2$ permanent plots, to replicate the sampling methodology of the interpreter.

We identified species and measured DBH of all trees ≥ 2.5 cm DBH on the nine Cockburn Island plots, and a random sample of up to three trees per form class (poplars, other hardwoods, pines, and other conifers) and crown class (dominant, codominant, intermediate, overtopped and/or suppressed, or understory) on the 80 permanent plots (Table 1). For sampled trees on permanent plots, we measured DBH, total tree height, height to base of live crown, crown class, and crown diameter along the crown's north-south and east-west axes. For a subset of tolerant and mid-tolerant hardwoods, we assessed tree quality using both six- and two-class systems (OMNR 2004).

We determined form (as for trees above) and decay class (using the 3-class system described previously), and measured DBH and height of each snag (Table 1). For downed wood, we determined decay class, and measured length and diameter at each end for pieces ≥ 10 cm diameter at the largest end.

### Analyses

We used descriptive statistics and simple linear regression to describe the nature of and compare differences between ground and photo measurements of plot and tree attributes. Comparisons were straightforward for all plot variables except canopy closure. As RMAP™ estimates of canopy closure for permanent plots were based only on the area of overlap between the 500 $m^2$ LSP plot and the 400 $m^2$ ground plot, the RMAP™ estimates were adjusted for area interpreted. Overlap areas ranged from 29 to 94% of the LSP plot. Exploratory analysis of these data showed that as overlap area decreased below 75%, the difference between the adjusted RMAP™ estimates of canopy closure and the ground estimates increased disproportionately, likely because a greater proportion of tree crowns were further from plot centre, where relief displacement may have biased crown measurements, as well as from sampling a smaller (i.e., less representative) area. We thus limited our comparison of LSP and ground canopy closure estimates to plots with 75% or more overlap; 16 plots qualified.

We examined differences in tree measurements for all co-registered trees as well as differences by form class or species where sample size permitted adequate statistical power ($1-\beta \geq 0.8$). As not all trees, snags, or downed wood were detected on photos, some could not be co-registered and were omitted from analyses. Comparisons based on the entire sample of co-registered trees thus reflected the greater proportion of trees sampled from the *other hardwood* form class and the codominant crown class. As fewer understory (i.e., overtopped or suppressed) trees were visible on photos, few trees from these crown classes were part of the co-registered sample. We used t-tests to compare size differences of detected and omitted features, and considered differences significant at $\alpha < 0.05$.

We assumed that ground measures were more accurate than LSP measures, since a field crew could directly observe and sometimes more directly measure a feature than could a photo interpreter. However, both ground and photo estimates are limited by equipment precision (Hall *et al.* 1993) and interpreter or field crew measurement precision (Omule 1980; McRoberts *et al.* 1994). Measurement precision also differs among variables. For example, species identification, and DBH are more repeatable measures than canopy closure, crown diameter, or tree height. Differences between ground and photo estimates or measures therefore are not entirely attributable to photo error.

## Results and Discussion

### Comparing leaf-off and leaf-on imagery

Optimal LSP interpretation and measurement conditions in Great Lakes-St. Lawrence mixed and hardwood forests occurred when leaves were absent. The leaf-off images taken mid-May, when most species had, or were about to break bud, were much easier to interpret than the images taken mid-July when leaves were present. In the leaf-on images, altitude readings, and thus photo scales, were unreliable for 43% of plots because the laser altimeter, a pulse LiDAR system, could not penetrate the foliage of dense canopies to return the high (canopy top) and low (ground) signals required to calculate altitude. Also, in leaf-on images, portions of canopy and sub-canopy trees were obscured. Foliage limited the interpreter's ability to detect trees and accurately delineate their crowns. The interpreter's ability to see the ground, and thus measure tree or snag heights accurately, was also

**Table 3.** *Descriptive and linear regression statistics of differences between ground and photo measurements of plot slope, aspect, and canopy closure. Linear regressions (ground measurement =f(photo measurement)) were significant (α < 0.001) with high statistical power (1-β > 0.8).*

| | Ground measurement | | | | Mean difference for paired ground/photo measurement | | Regression equation | | Regression statistics | |
|---|---|---|---|---|---|---|---|---|---|---|
| Variable | n | Median or Mean (Std. Dev.)[a] | Min | Max | MPD[b] | Std. Dev. | Intercept (p-value) | Slope (p-value) | RMSE[c] | $r^2$ |
| Slope (%) | 79 | 13.0 | 0 | 47 | 7.4 | 5.5 | 0.15 (p=0.9) | 0.75 (p<0.001) | 7.7 | 0.59 |
| Aspect (°) | 51 | N/A (circular distribution) | | | 36.9 | 33.3 | 20.8 (p=0.06) | 0.87 (p<0.001) | 48.0 | 0.82 |
| Canopy closure (%) | 16 | 64.9 (15.2) | 35 | 84 | 18.2 | 9.8 | 21.8 (p<0.001) | 0.92 (p<0.001) | 10.1 | 0.59 |

[a] Median for non-normal distribution, mean (with standard deviation) for normal distribution

[b] Mean paired difference (absolute value) calculated as MPD = |(ground measure) – (photo measure)|

[c] Root mean squared error, or standard error of the estimate

impaired. Further, the higher contrast conditions of the July photos meant that the ground was more difficult to see in the few canopy gaps present, relative to May photos.

We hypothesized that leaf shape and foliage colour, visible in leaf-on imagery, would improve tree species identification, but found the branching pattern and bark characteristics, which were more visible in leaf-off images, to be of greater value. Inter-specific differences in phenology, apparent in the May photos, also helped the interpreter to differentiate species. For example, the burst, bright-green buds of trembling aspen helped distinguish them from balsam poplar. Likewise red maple's red flowers and buds contrasted with the darker buds of sugar maple. The value of phenology to hardwood species identification on air photos has been described previously (Sayn-Wittgenstein 1960, 1961; Aldred and Hall 1975).

Phenology is highly variable so timing LSP to capture particular events can be difficult. Phenological differences result from species, site (including weather), and tree (including age and vigour) factors (Sayn-Wittgenstein 1960). Inter-specific differences in phenology at one location may not be simultaneously evident at another location. For this study, leaf-off images were captured over a two-day period in mid-May. Species differed dramatically between Algoma (relatively advanced) and Cockburn Island (delayed) plots, and slightly among Algoma plots. Further, inter-annual variation in phenology, attributable to spring weather, could make advance planning difficult.

Autumn leaf-off photography is another option for hardwood forests, but weather conditions for flying LSP missions tend to be more favourable in the spring, and the opportunity to capture images in advance of summer field work, makes spring photography more desirable.

## Assessing targeting accuracy

Target accuracy is essential for accurate resampling of permanent sample plots. We attempted to capture the plot centre of permanent plots within 5 m of the LSP centre (Figure 3). We prescribed the target bubble of 5 m (i.e., cameras were enabled to fire when the helicopter was within 5 m of the target) to achieve 80% or greater overlap between the 500 $m^2$ LSP plot and the 400 $m^2$ ground plot. With less overlap, the suitability of LSPs for permanent plot applications diminishes. Actual distance (error) between plot centre and LSP centre ranged from 1.61 to 22.21 m. At these distances, overlap between the LSP plot and ground plot ranged from 99% to

3%, respectively. Mean target error was 8.70 ± 4.17 m, resulting in 61% overlap of LSP and ground plots. Mean and maximum target errors would likely increase with target bubble size.

Cumulative GPS-related errors were suspected to reduce targeting accuracy. Plot centre coordinates could have been more accurately obtained through post correction of GPS locations. Accuracy may have improved with establishment of permanent survey points (Kovats 1997), and/or visual targeting by the pilot. Improved accuracy is likely possible, but could require additional time, effort, and expense (Pitt *et al.* 2000).

The helicopter's GPS antenna is located on the cockpit roof, under the main rotor (Figure 2). Since the cameras fire when the helicopter's distance to target begins to increase, as the helicopter travels forward, the rear camera captures a greater proportion of the plot than the front camera. The mean distance between the rear principal point and the ground target was significantly less, 8.22 ± 4.47 m, than that between the front principal point and the ground target, 9.97 ± 4.62 m ($F = 3.033$, $p = 0.0365$). Establishing the LSP photo centre at the stereo centre—halfway between the front and rear principal points—is optimal for providing the most stereo coverage for interpretation. Establishing the LSP photo centre at a principal point is easier for an interpreter; however, because the rear principal point captures more of the ground plot than the front principal point, the rear is a better choice.

## Measuring plot-level features

Highly variable, undulating or mounded microtopography made LSP and ground assessment of slope and aspect difficult for many plots. On photos, obstructed ground visibility from buds, branches, or entire trees, made interpreting slope and aspect that much more difficult.

Ground- and LSP-measured slopes were only marginally well correlated, but ground- and LSP-measured aspects were similar for plots with ground-measured slopes greater than 5% (Table 3). Differences between ground- and LSP-measured aspects tended to diminish with increasing slope; more visible and obvious differences in slope coincided with closer ground- and LSP-measured aspects. We anticipate better relationships on less undulating terrain. LSP may be useful for describing plot microtopography (e.g., for ecosystem description).

Ground estimates of canopy closure vary substantially depending on assessment methodology. In this study, ground estimates exceeded LSP estimates and the two were only marginally correlated (Table 3). The marginal relationship between the two estimates would likely have improved with larger sample size, sampling the forest under the same conditions (e.g., both measured leaf-off), and interpreting the entire LSP plot, rather than correcting RMAP™ values for area interpreted.

We did not evaluate the re-measurement precision of canopy closure estimates from photos, but if there had been high re-measurement precision, the photos could provide measures of canopy closure that are more consistent than ground methods. LSP measurements of crown properties elsewhere have been useful in studies of crown dynamics (Herwitz *et al.* 2000).

## Detecting trees, snags, and downed wood

Trees of different form and crown classes occurred at different frequencies, and were detected at different rates (Table 4). Tree (≥ 2.5 cm DBH) densities ranged from 35 to 88 stems per 500 $m^2$ plot over nine Cockburn Island plots; 49 to 77% (mean 66%) of these trees were detected. The interpreter detected all dominants and most codominants, and fewer of the intermediate, understory, and overtopped or suppressed trees (Table 4). The most economically important trees to sample in the short-term, the dominants and codominants, were almost always detected. For many applications, enumerating all understory trees, which contribute less to stand volume, could be less important than determining their species composition.

The interpreter detected higher percentages of *poplar* and *pine* than *other hardwoods* or *other conifers*, but all the *poplars* and *pines* were dominant or canopy (codominant or intermediate) trees (Table 4). Of the intermediate form class, the taller, shade-intolerant (and thus open-growing) *poplars* and the green *other conifers* were easier to detect than the faint, sometimes shaded, *other hardwoods*. Understory trees, by definition, were shorter and often obscured by overstory trees. *Other hardwoods* in the understory appeared only faintly; they were especially difficult to see against the backdrop of the forest floor and under taller hardwoods. While *other conifers* were visible under a hardwood canopy, delineating individual crowns from regenerating patches was difficult.

Even large *other conifers* were sometimes clumped, making the delineation of individual crowns more difficult, and increasing the commission error rate (i.e., incorrectly delineating trees that do not exist), as discussed by other researchers (Hall and Aldred 1992; Pitt *et al.* 1997). Delineation errors of *other hardwoods* typically occurred when multiple trees were delineated as one tree or, less commonly, when one tree was interpreted as two or more trees (Table 4). These commission errors were often attributable to differences in definition; the interpreter sometimes delineated multiple trees that forked below 1.3 m as a single tree, and single trees that forked above 1.3 m as multiple trees.

Forest structure and composition affect ease of detection. In even-age stands with uniform species composition, we would anticipate greater similarity between ground and LSP counts (Needham and Smith 1987); in multi-storied forests with more closed canopies, we would anticipate greater disparity (Herwitz *et al.* 2000). Despite the uneven-aged and hardwood-dominated composition of Cockburn Island plots, mean tree detection was the same as that from an LSP (1:500) study of conifer regeneration in mixed boreal cutovers of Saskatchewan where interpreters detected 66% of conifers (Hall and Aldred 1992). When more accurate tree densities are required from LSP-based inventories, LSP tallies could be calibrated (Hall and Aldred 1992).

As with trees, larger snags tended to be more evident on LSPs. Snag (≥ 10 cm DBH) densities from 14 old-growth and nine Cockburn Island plots ranged from 1 to 12 per 500 $m^2$ plot (Table 5). Of 96 snags, the interpreter detected 41 (43%), two of which he misidentified as trees. The interpreter also misidentified two additional trees as snags.

***Table 4.*** *A. Photo interpreted tree detection rates by form class and crown class for nine Cockburn Island plots. B. Photo interpreted tree delineation error rates for detected trees.*

| Form class | Crown class | | | | | |
|---|---|---|---|---|---|---|
| | Dominant | Codominant | Intermediate | Overtopped/ Suppressed | Understory | Total |
| **A.** Detection rates (n) | | | | | | |
| Poplars | 100% (13) | 100% (15) | 100% (3) | – (0) | – (0) | **100% (31)** |
| Other hardwoods | 100% (5) | 95% (83) | 64% (28) | 40% (25) | 27% (67) | **63% (208)** |
| Pines | 100% (7) | 100% (3) | – (0) | – (0) | – (0) | **100% (10)** |
| Other conifers | 100% (5) | 97% (60) | 80% (64) | 31% (94) | 62% (125) | **64% (348)** |
| **Total** | **100% (30)** | **96% (161)** | **76% (95)** | **33% (119)** | **50% (192)** | **66% (597)** |
| **B.** Delineation error rates (n) | | | | | | |
| Poplars | | | | | | |
| • 2+ trees interpreted as 1 | 8% | 7% | – | – | – | **6%** |
| • 1 tree interpreted as 2+ | 8% | – | – | – | – | **3%** |
| Other hardwoods | | | | | | |
| • 2+ trees interpreted as 1 | – | 7% | – | – | – | **3%** |
| • 1 tree interpreted as 2+ | – | – | – | – | – | **–** |
| Pines | | | | | | |
| • 2+ trees interpreted as 1 | – | – | – | – | – | **–** |
| • 1 tree interpreted as 2+ | – | – | – | – | – | **–** |
| Other conifers | | | | | | |
| • 2+ trees interpreted as 1 | – | 2% | 3% | 2% | <1% | **2%** |
| • 1 tree interpreted as 2+ | – | – | – | 1% | – | **<1%** |
| **Total** | **7%** | **5%** | **2%** | **3%** | **<1%** | **3%** |

Detected snags were significantly taller ($t = 5.237$, $P < 0.001$; Figure 4a) and had larger DBH ($t = 2.544$, $P = 0.013$; Figure 4b) than omitted snags. These larger snags may have occupied more crown space as live trees, ensuring larger openings around them for a longer time. Smaller snags would either have been smaller trees in smaller openings or, if they were decayed larger trees, had been dead for a longer time enabling more of the surrounding canopy to close around them, and reducing their visibility to an interpreter.

Larger snags are more important for wildlife; they last longer and can be used by a greater variety of organisms (Cline *et al.* 1980). One study in northeastern Ontario has shown that cavity-nesting birds only used snags ≥ 15 cm DBH, and used increasing proportions of larger diameter snags if available (Spytz 1993). In our study, detection of snags ≥ 15 cm DBH was greater (50%) than for snags ≥ 10 cm DBH (43%).

As with snags, there were substantial differences among plots in occurrence and detection of downed wood. Downed wood (≥ 10 cm diameter) frequencies ranged from 1 to 24 pieces per plot over the 17 plots we examined and rates of detection ranged from 0 to 88% (Table 5).

Detected and omitted downed wood did not differ significantly in length ($t = 1.266$, $P = 0.208$) or largest diameter ($t = 0.584$, $P = 0.560$), but detection may have been affected by photo contrast and quality, forest structure, overstory and understory compositions, forest floor colour, and state of decay. As we had a small, unstratified sample, we could not test these factors for effects on detection rates.

## Identifying tree species and snag form class

The range of tree species, crown sizes, and crown layers of mature Great Lakes-St. Lawrence forests can make identifying tree species in photos challenging (Sayn-Wittgenstein 1960). Of 997 live trees (≥ 2.5 cm DBH) co-registered on Algoma and Cockburn Island plots, the interpreter correctly identified 99% to form class and 82% to species (Table 6). The interpreter easily distinguished among form classes. *Poplars* were distinguished from *other hardwoods* by their "lollipop," more regular and rounded crowns than *other hardwoods*. *Pines* were distinguished from *other conifers* by stature, crown shape, and needle appearance.

Some species were easier to identify in the photos than others. Of the *poplars*, trembling aspen was more frequently identified as balsam poplar than vice versa. Since aspen buds had burst for most trees, the interpreter may have misidentified delayed aspen trees as balsam poplar, which typically had closed buds. Among the *other hardwoods*, white birch was almost always identified correctly, whereas other species encountered less

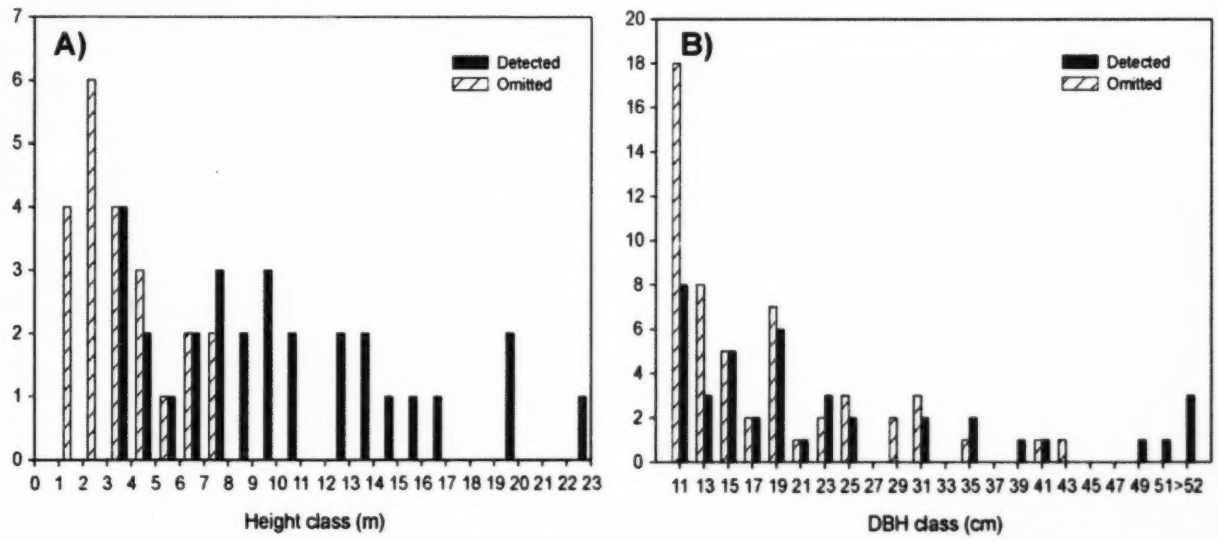


***Figure 4.*** *(a) Height and (b) DBH distributions of detected (black) and omitted (patterned) snags (≥ 10 cm DBH). Height was measured for 29 detected and 22 omitted snags on 14 old-growth plots. DBH was measured for 41 detected and 55 omitted snags on 14 old-growth and 9 Cockburn Island plots.*

***Table 5.*** *Frequencies of snags (≥10 cm DBH) and downed wood (≥10 cm largest diameter) by plot.*

| Plot subset | Plot number | Snags | | Downed wood[a] | |
|---|---|---|---|---|---|
| | | Ground | Photo | Ground | Photo |
| Forest Ecosystem Classification | FEC 988 | – | – | 11 | 8 |
| | FEC 1220 | – | – | 11 | 9 |
| | FEC 1221 | – | – | 24 | 8 |
| Old growth | OG 1 | 5 | 2 | 4 | 1 |
| | OG 2 | 3 | 1 | 8 | 4 |
| | OG 3 | 3 | 1[b] | 3 | 2 |
| | OG 4 | 2 | 2 | 8 | 7 |
| | OG 5 | 2 | 1 | 9 | 7 |
| | OG 6 | 1 | 0 | 9 | 4 |
| | OG 7 | 9 | 4[c] | 14 | 3 |
| | OG 9 | 9 | 8 | 8 | 2 |
| | OG 10 | 4 | 3 | 4 | 1 |
| | OG 11 | 3 | 2 | 4 | 3 |
| | OG 12 | 2 | 2 | 9 | 4 |
| | OG 13 | 2 | 0 | 3 | 2 |
| | OG 14 | 4 | 3 | 1 | 0 |
| | OG 15 | 2 | 0 | 5 | 0 |
| Cockburn Island | L001_004 | 1 | 0 | – | – |
| | L004_011 | 7 | 0 | – | – |
| | L006_015 | 7 | 0 | – | – |
| | L006_016 | 12 | 3 | – | – |
| | L014_041 | 1 | 0 | – | – |
| | L014_043 | 2 | 2 | – | – |
| | L014_044 | 2 | 2[b] | – | – |
| | L029_082 | 9 | 4[c] | – | – |
| | L038_109 | 4 | 1 | – | – |
| **Total** | | **96** | **41** | **137** | **67** |

a. Downed wood frequencies are higher in FEC plots than in old growth plots because the entire 500 m² photo plot was surveyed for downed wood, while in the old growth plots, two orthogonal transect lines of 20 m were surveyed.

b. 1 snag misidentified as live tree

c. 1 live tree misidentified as snag

frequently and with less unique (leaf-off) attributes, such as American beech (*Fagus grandifolia* (Ehrh.) Little), ironwood, black cherry, and northern red oak (*Quercus rubra* L.), tended to be misidentified as the more common species they resembled, i.e., sugar maple or yellow birch.

*Pine* misclassification seemed to result from atypical crown position (e.g., understory) or atypical form (e.g., sparse foliage). Similarly, conifer misidentifications on large-scale photos of coastal and interior BC forests tended to be trees of either atypical form or association (Lyons 1967).

Since conifers have more definite and characteristic shapes, they tended to be more easily recognized than *other hardwoods*, which have more variable forms and crown shapes. Among the *other conifers*, spruces were sometimes difficult to distinguish from balsam fir, and hemlock was at times difficult to distinguish from balsam fir or eastern white cedar. Only a few eastern larch (*Larix laricina* (Du Roi) K. Koch) occurred in study plots. These were all identified correctly owing to their distinct appearance.

Of 56 snags, 93% were correctly identified to form class (Table 6). As with live trees, snags of different form classes occurred with different frequencies. No more than one snag of any species was misidentified to form class.

Some misidentifications of tree or snag form class, such as a red maple tree interpreted as a white pine, were likely due to errors selecting species from the RMAP™ menu. The version of RMAP™ available for this study did not permit editing a data record once created, so an incorrect selection would require the interpreter to re-do the entire plot if the species error was noticed. Until RMAP™ is modified to allow the interpreter to easily correct the species selection, extreme care must be used by the interpreter to select the correct species on the digitizing tablet. Consideration should be given to instructing the interpreter to re-enter a record if he or she discovers that an incorrect species selection was made.

Results are likely to vary with photo timing and quality, weather conditions, film type, and printing and developing qualities. For example, spruce and balsam fir may be better distinguished with infrared-film photography (Sayn-Wittgenstein 1961). Our results are similar to a study in mixed forests at Petawawa where 99.6% of trees were correctly identified to pine, spruce or fir, and hardwood form classes, and 89.6% of conifers were correctly identified to species (Aldred and Kippen 1967).

## Classifying ecosites

From the interpreted species composition and FRI-to-FEC conversion software (Naylor and Chambers, n.d.), which uses an algorithm to relate tree species composition to ecosite, ecosite was predicted reasonably well. Photo-derived ecosites were correct for 74% of the 43 plots we evaluated (Table 7) and species compositions of misidentified ecosites were similar to actual ecosites.

Among Ontario's regional Forest Ecosystem Classifications (FECs), the Central Region is unique because ecosites may be keyed based only on overstory

species composition. In other regions, where additional vegetation, landform, and soil information are required to determine ecosite, LSPs could be a useful predictive tool, but would have to be combined with ground-validated medium-scale photography or satellite imagery for verification (Befort 1986; Arnup *et al.* 1999). For ecosystem classification over a larger spatial scale, LSPs could be combined with smaller scale imagery in either coarse to fine or fine to coarse approaches (Sandmann and Lertzman 2003).

## Measuring tree height

Tree heights of ground and LSP co-registered trees ranged from 2.13 to 26.95 m (ground measures) and overall, the ground and LSP measurements were similar (Table 8). Form classes differed in sample size, tree form and appearance, and range of tree heights; factors that likely affected their height regression relationships (Table 8).

The *poplars* had a slightly stronger coefficient of determination ($r^2$) than *other hardwoods*, but a weaker $r^2$ than *pines* or *other conifers*. Only 14 *poplars* were co-registered, and although these trees had regular crown forms and often had flushing buds, their faint treetops were more difficult for both the interpreter and the ground crews to discern, than the green tops of other conifers. *Poplars* also comprised the tallest form class. Since tall trees are more difficult to measure from the ground as they are often obscured by other crowns and require the observer to be further from the tree for measurement, it was not surprising that the *poplars* had a weaker relationship than the *other conifers* or *pines*.

Discerning the faint tops of *other hardwoods* was made more difficult by their spreading crown forms. The *other hardwoods* had the largest sample size, making up 74% of our sample, but the poorest model fit. The average difference in height between ground and LSP heights measured for *other hardwoods* in this study was 75 cm larger than the 1.13 m difference measured in mixed forests at Petawawa (Aldred and Kippen 1967).

The contrasting green foliage and apical form of *pines* and *other conifers* generally allowed the interpreter and field crews to more easily discern and measure treetops, so the differences between ground and LSP-measurements for these form classes were smaller than for *poplar* and *other hardwoods* classes (Table 8). Although only 17 *pines* were co-registered, this form class had the best model fit (lowest RMSE and highest $r^2$). The mean difference in ground and LSP heights for *other conifers* in this study was 40 cm larger than that for the 70 cm difference measured for conifers (> 10 m) reported by Aldred and Hall (1975). However, the large proportion of sub-canopy balsam fir that comprised the *other conifers,* many less than 10 m tall, likely weakened the relationship for this form class because shorter, sub-canopy trees are nearly always more difficult for the interpreter to identify and measure.

Not surprisingly, the interpreter had a more difficult time discerning base of live crown (BLC) than total height. Overall, the relationship between ground and photo BLC was marginal (Table 8). As with total height, the BLC sample was weighted heavily by the large proportions of *other hardwoods* and *other conifers*, both with weaker relationships. *Other hardwoods* lacked foliage that contrasted with ground cover, and the lower branches that were visible appeared only faintly. *Pines* exhibited a better relationship between ground-measured and photo-interpreted BLC heights. These trees had distinct foliage and clear boles. Most *other conifers* did not have clear boles, so their crown bases were not distinct. As well, a large proportion of the *other conifers* were smaller sub-canopy trees that were more difficult for the interpreter to measure. Discerning crown base is confounded in multi-storied forests as bottoms of sub-canopy trees are easily confused with those of other trees in lower levels. Leaf-off images further make the task of separating crowns difficult because branches appear faintly against the backdrop of the previous season's leaf fall. The *poplars* had insufficient sample size, and thus statistical power, to analyse BLC.

Given the marginal relationship between ground- and LSP-measured height to BLC for all but the *pine* form class, it also was not surprising that ground and LSP live crown ratios (LCR) were not correlated well overall (Table 8). All four form classes lacked sufficient statistical power to report regression results.

Ground- and photo-measured snag heights were strongly correlated, but not as well as for live trees (Table 8), possibly due to the smaller sample size of snags. As well, mean snag height was lower than that of live trees, so snag height may have been more difficult for the interpreter to measure.

***Table 6**. Rates of **A**. trees correctly identified to species from 80 (permanent) Algoma and nine Cockburn Island plots, and **B**. snags correctly identified to form class from 80 Algoma, nine Cockburn Island, and 14 old-growth plots. Misidentification types for form class and species for trees and snags are shown with associated frequencies in parentheses.*

| Status | Form class | Species[a] | Co-registered (No.) | Correctly identified (%) | Misidentification type | |
|---|---|---|---|---|---|---|
| | | | | | Form class | Species |
| **A. Trees** | Poplars | *Balsam poplar, Pb* | 9 | 89% | | Pt(1) |
| | | *Trembling aspen, Pt* | 29 | 69% | By(1) Bw(1) | Pb(7) |
| | | Populus spp., Po | 6 | 100% | | |
| | | Poplar total | 44 | 77% | | By(53) Mr(20) Or(5) |
| | Other hardwoods | Sugar maple, Mh | 427 | 81% | Pt(1) | Aw(3) Bw(1) |
| | | Red maple, Mr | 47 | 72% | Pw(2) | Mh(10) By(1) |
| | | Yellow birch, By | 55 | 78% | | Mh(12) |
| | | White birch, Bw | 51 | 96% | Pt(2) | |
| | | Northern red oak, Or | 13 | 23% | | Mh(7) By(2) Mr(1) |
| | | American beech, Be | 10 | 0% | | Mh(10) |
| | | *White ash, Aw* | 5 | 80% | | Mr(1) |
| | | *American elm, Ew* | 1 | 0% | | By(1) |
| | | *Ironwood, Iw* | 8 | 0% | | By(7) Mh(1) |
| | | Black cherry, Cb | 1 | 0% | | By(1) |
| | | Other hardwood total | 618 | **77%** | | |
| | Pines | White pine, Pw | 25 | 80% | Bf(3) Mr(1) | Pr(1) |
| | | Red pine, Pr | 3 | 100% | | |
| | | Pine total | 28 | **82%** | | |
| | Other conifers | Balsam fir, Bf | 182 | 94% | Pw(1) | Sw(7) Cw(3) |
| | | White spruce, Sw | 19 | 63% | | Bf(7) |
| | | *Black spruce, Sb* | 4 | 0% | | Sw(4) |
| | | *Eastern hemlock, He* | 21 | 67% | | Bf(3) Cw(3) Sw(1) |
| | | Eastern white cedar, Cw | 78 | 96% | Pw(1) | He(1) Bf(1) |
| | | *American larch, La* | 3 | 100% | | |
| | | *Other conifer total* | **125** | **90%** | | |
| | **Total** | | **997** | **81%** | | |
| **B. Snags** | Poplars | Trembling aspen, Pt | 1 | 100% | | |
| | | Poplar total | 1 | **100%** | | |
| | Other hardwoods | Sugar maple, Mh | 17 | 94% | Pines(1) | |
| | | Red maple, Mr | 4 | 75% | Other conifers(1) | |
| | | Yellow birch, By | 1 | 100% | | |
| | | White birch, Bw | 9 | 89% | Other conifers(1) | |
| | | Other hardwood total | 31 | **90%** | | |
| | Pines | White pine, Pw | 1 | 100% | | |
| | | Pine total | 1 | **100%** | | |
| | Other conifers | Balsam fir, Bf | 19 | 95% | Poplars(1) | |
| | | White spruce, Sw | 2 | 100% | | |
| | | Black spruce, Sb | 1 | 100% | | |
| | | Eastern white cedar, Cw | 1 | 100% | | |
| | | Other conifer total | **23** | **96%** | | |
| | **Total** | | **56** | **93%** | | |

[a] Because some species occurred relatively infrequently on sample plots or were not sampled during the crown diameter-DBH regression field work (shown in italics), the interpreter had little (e.g., Aw) or no (e.g., Iw, Cb) specific training to identify these.

The interpreter noted that photo quality, phenology, and tree position affected his certainty in height measurements. Hardwood treetops were easier to see in photos taken under overcast conditions because shadows were minimized. A small amount of bud colouration and leaf flush also enhanced the interpreter's ability to identify branch tips of some hardwoods. The interpreter was more easily able to distinguish BLC as tree distance from photo centre, and thus relief displacement, increased.

Topography, tree heights, and forest species composition also affect overall measurement precision. Trees of larger sizes, on more sloping terrain, are more difficult to measure reliably on photos (Lyons 1967) and, even on level ground, pits and mounds can make ground assessment of elevation, and therefore tree height measurements, difficult.

## Measuring tree crown diameter

Ground and LSP measurements of crown diameter were moderately well correlated (Table 9). As with trees sampled for height, a large proportion of the crown diameter sample was made up of *other hardwoods* (75%), which had poorer model fit than other form classes. As well, more than half of the trees sampled were in dominant or codominant crown classes and thus had large crowns.

Differences between ground- and LSP-measured crown diameters reflected differences in the interpreter's ability to discern crown edge, and in the regularity of crown shape. *Other hardwoods* had the most irregular crowns, and their typical codominant crown positions meant that crowns overlapped and were more difficult for both the interpreter and field crews to measure. Model fit improved for *pines* and *other conifers* (Table 9). Edges of *pine* crowns were easy to discern on photos because these trees mostly occupied upper canopy positions and had distinctive foliage. *Other conifers* had regular crown shapes and foliage, but often occupied lower canopy positions where they were obstructed by the overstory or grew in clumps.

***Table 7.*** *Comparison of central Ontario ecosite classifications (Chambers et al. 1997) from 43 permanent sample plots in Algoma. Photos were classified using interpreted species composition and predictive software. Numbers of plots for each ecosite are given in square brackets. Bold-faced ecosites were correctly predicted.*

| Field-determined ecosite [No. plots of that type in sample] | | Predicted ecosite from photo-interpreted tree species composition for same plot [No. plots of that type predicted] | |
|---|---|---|---|
| 17.2 | Poplar-white birch (fresh to moist) [1] | 21 | White cedar-white pine-white birch-white spruce [1] |
| 21.2 | White cedar-white pine-white birch-white spruce (fresh to moist) [1] | **21** | White cedar-white pine-white birch-white spruce [1] |
| 28.1 | Sugar maple-hemlock-yellow birch (dry to moderately fresh) [1] | 29 | Sugar maple-yellow birch [1] |
| 28.2 | Sugar maple-hemlock-yellow birch (fresh to moist) [6] | 29<br>17 | Sugar maple-yellow birch [5]<br>Poplar-White birch [1] |
| 29.1 | Sugar maple-yellow birch (dry to moderately fresh) [12] | **29** | Sugar maple-yellow birch [12] |
| 29.2 | Sugar maple-yellow birch (fresh to moist) [19] | **29**<br>30<br>25 | Sugar maple-yellow birch [17]<br>Hemlock-yellow birch [1]<br>Sugar maple-beech-red oak [1] |
| 31 | Black spruce-tamarack [1] | 32 | White cedar-black spruce-tamarack [1] |
| 32 | White cedar-black spruce-tamarack (very moist to wet) [1] | **32** | White cedar-black spruce-tamarack [1] |
| 33 | White cedar-other conifer (very moist to wet) [1] | **33** | White cedar-other conifer [1] |

***Table 8.*** *Descriptive and linear regression statistics for ground and photo measurements of tree height, height to base of live crown (BLC), live crown ratio (LCR), and snag height. Linear regressions (ground measurement =f(photo measurement)) were significant (α < 0.001) with high statistical power (1-β > 0.8).*

| | Ground measurement | | | | | Ground - photo | | Regression equation | | Regression statistics | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | N | Mean | St. Dev. | Min. | Max. | Mean paired | St. Dev. | Intercept[a] | Slope[b] | RMSE[c] | $r^2$ |
| **Tree height (m)** | **476** | **16.34** | **5.79** | **2.13** | **26.95** | **1.68** | **1.51** | **2.10** | **0.861** | **2.08** | **0.872** |
| *Poplars* | 14 | 18.92 | 3.51 | 14.00 | 24.60 | 1.37 | 0.77 | 0.68* | 0.975 | 1.66 | 0.793 |
| *Other Hardwoods* | 353 | 18.17 | 4.03 | 7.80 | 26.95 | 1.88 | 1.60 | 4.84 | 0.722 | 2.06 | 0.740 |
| *Pines* | 17 | 14.35 | 7.54 | 4.73 | 25.90 | 0.95 | 0.69 | 0.54* | 0.955 | 1.17 | 0.977 |
| *Other Conifers* | 92 | 9.27 | 5.93 | 2.13 | 23.80 | 1.11 | 1.09 | 0.23* | 0.986 | 1.56 | 0.932 |
| Sugar maple | 244 | 18.88 | 3.96 | 7.80 | 26.95 | 1.93 | 1.66 | 5.09 | 0.707 | 2.04 | 0.736 |
| Red maple | 26 | 15.94 | 3.13 | 11.88 | 23.34 | 1.82 | 1.11 | -0.36* | 1.015 | 2.21 | 0.521 |
| Yellow birch | 40 | 16.46 | 3.94 | 9.10 | 23.69 | 1.97 | 1.98 | 5.82 | 0.680 | 2.24 | 0.685 |
| White birch | 23 | 16.72 | 3.67 | 10.10 | 22.20 | 1.62 | 0.86 | 2.64* | 0.869 | 1.76 | 0.780 |
| Northern red oak | 13 | 19.30 | 4.00 | 8.20 | 23.90 | 1.55 | 1.20 | 3.24* | 0.851 | 1.94 | 0.785 |
| White pine | 14 | 11.98 | 5.97 | 4.73 | 23.78 | 1.04 | 0.72 | 0.63* | 0.945 | 1.30 | 0.956 |
| Balsam fir | 63 | 7.12 | 4.87 | 2.13 | 17.60 | 0.99 | 0.87 | 0.31* | 0.958 | 1.32 | 0.928 |
| White spruce | 12 | 15.20 | 7.25 | 3.15 | 23.80 | 1.20 | 1.16 | 0.54* | 0.961 | 1.77 | 0.946 |
| Eastern white cedar | 10 | 12.39 | 3.13 | 8.60 | 17.60 | 1.21 | 0.87 | -0.033* | 0.984 | 1.62 | 0.764 |
| **Base of live crown (m)** | **285** | **6.47** | **4.63** | **0.00** | **16.95** | **2.14** | **2.09** | **0.40*** | **0.884** | **2.94** | **0.599** |
| *Poplars* | 12 | 13.81 | 1.81 | 11.20 | 16.90 | 2.95 | 1.68 | | | | |
| *Other Hardwoods* | 168 | 8.15 | 3.79 | 0.38 | 16.95 | 2.40 | 2.21 | 2.50 | 0.667 | 3.07 | 0.348 |
| *Pines* | 16 | 6.69 | 4.79 | 1.70 | 15.27 | 1.57 | 0.18 | 0.37* | 0.942 | 2.29 | 0.787 |
| *Other Conifers* | 89 | 2.25 | 2.63 | 0.00 | 10.10 | 1.64 | 1.90 | 0.24* | 0.606 | 1.98 | 0.443 |
| **Live crown ratio** | **285** | **0.60** | **0.21** | **0.13** | **1.00** | **0.15** | **0.13** | **0.19** | **0.758** | **0.19** | **0.260** |
| *Poplars* | 12 | 0.26 | 0.10 | 0.13 | 0.47 | 0.14 | 0.08 | | | | |
| *Other Hardwoods* | 168 | 0.54 | 0.17 | 0.18 | 0.97 | 0.14 | 0.13 | | | | |
| *Pines* | 16 | 0.25 | 0.18 | 0.16 | 0.90 | 0.11 | 0.10 | | | | |
| *Other Conifers* | 89 | 0.79 | 0.18 | 0.19 | 1.00 | 0.18 | 0.12 | | | | |
| **Snag height (m)** | **58** | **10.96** | **4.87** | **3.61** | **24.93** | **1.62** | **1.66** | **0.10*** | **0.924** | **2.19** | **0.810** |

[a] Intercept coefficients marked with * have non-significant p-values (> 0.05); all other coefficients have significant p-values (< 0.05)

[b] All slope values have significant p-values (< 0.001)

[c] Root mean squared error or standard error of the estimate

The high proportion of *other hardwoods*, the overlapping condition of trees from multiple layers, and discrepancies between ground- and photo-measurement protocols, all contributed to weakened crown diameter relationships. The *other hardwoods* had irregular crowns that were less predictable and more difficult to trace than other form classes. Their crowns often overlapped, but so did those of *other conifers*, particularly in regenerating patches. Species composition will thus affect how well ground and LSP measurements of crown diameter relate (Pitt et al. 1996).

Good relationships between ground- and photo-measures of crown dimensions are not only useful for DBH or volume estimates, but may be applied to hardwood silviculture practices where standard ground measurements can be highly variable, time-consuming, and difficult for field personnel (Herwitz *et al.* 2000). Crown diameter measurements would likely have improved substantially if the ground- and photo-measurement protocols were more similar in our study, especially with respect to measurement season and crown diameter measurement protocols. Project timing limitations made it necessary to conduct ground sampling in leaf-on conditions, but our primary photo interpretation images were leaf off, creating possible discrepancies in crown size measurements between leaves and twig ends. Ground measurements of tree crown diameter were based on two measurements (north-south and east-west axes through the geometric centre of the crown), while photo measurements were calculated as the diameter of a circle computed from the crown perimeter as delineated by the interpreter.

## Measuring tree diameter at breast height

As with crown diameter, ground-measured and LSP-derived DBH were reasonably well correlated (Table 9). More trees were sampled for DBH than for crown diameter, and the proportions of trees by form class also differed; the sample comprised relatively more *poplars* and *other conifers*. As well, the DBH sample included more trees from lower canopy classes.

Ground measurements and LSP estimates of DBH were more highly correlated for *poplars*, *pines*, and *other conifers* than for *other hardwoods*, the form class with the most irregularly shaped crowns and stems (Table 9). The regression equations that related crown diameter and height measurements to DBH also exhibited better fit for *poplars*, *pines*, and *other conifers* than for *other hardwoods* (Table 2). Unlike crown diameter, however, the root mean square error (RMSE) of *other conifers*, particularly balsam fir, was almost as high as that of *other hardwoods*. The DBH sample included trees from Cockburn Island where a greater effort was made to co-register trees of lower crown classes, which were not well represented in the development of the original regression equations (Table 2). The crown diameter sample did not include as many of these smaller conifers.

Poor relationships may have improved by sampling trees in the range of sizes that were co-registered. Species-specific regression equations predicting DBH from tree height and crown diameter performed well for trees of mid-range DBH growing on typical sites. Very small or very large trees, and those growing on less typical sites, were likely not included in regression sampling, resulting in equations that did not predict their diameters as well or exhibited unrealistic model behaviour within expected DBH ranges. For example, the photo-predicted DBHs for some very small (but $\geq$ 2.5 cm DBH) *other conifers* were negative.

Coefficients of determination for most species we evaluated were within the range of those photo-predicted for British Columbia interior and coastal conifer species (Lyons 1967), but relative root mean square errors in this study (RMSE as a percentage of the mean) tended to be higher. The conifers in the other study were larger, however, so the same absolute differences would result in smaller relative differences.

## Measuring downed wood

Ground-measured lengths of downed wood ranged from 0.6 to 18.2 m. Although the photo measurements tended to overestimate downed wood lengths, ground- and photo-derived lengths were still significantly correlated ($r^2 = 0.875$) (Table 10).

Ground-measured diameters of downed wood ranged from 4.0 to 72.3 cm for the butt end of the log and 1.6 to 30.1 cm for the top end. Both butt and top diameter measurements had weaker relationships with photo measurements and had higher RMSEs than did length measures (Table 10). There were fewer diameter measures than length measures, which may have contributed to the lower correlations between ground and photo measures of downed wood diameter.

Downed wood diameters from our plots tested the limits of photo-measurement precision. To distinguish 5-cm classes on 1:430 photos, an interpreter has to be able

***Table 9.*** *Descriptive and linear regression statistics for ground- and photo-measurements of tree crown diameter and DBH by form class and species. Linear regressions (ground measurement =f(photo measurement)) were significant ($\alpha < 0.05$) with high statistical power ($1-\beta > 0.8$).*

| | Ground measurement | | | | | Ground - photo | | Regression equation | | Regression statistics | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | N | Mean | St. Dev. | Min. | Max | Mean paired | St. Dev. | Intercept[a] | Slope[b] | RMSE[c] | $r^2$ |
| **Crown diameter (m)** | **379** | **5.45** | **2.40** | **1.12** | **12.64** | **1.13** | **1.02** | **1.65** | **0.789*** | **1.27** | **0.720** |
| Poplars | 7 | 3.18 | 0.83 | 2.04 | 4.32 | 0.45 | 0.20 | Non-significant regression | | | |
| Other Hardwoods | 285 | 6.15 | 2.21 | 11.39 | 12.64 | 1.34 | 1.07 | 2.46 | 0.688 | 1.30 | 0.657 |
| Pines | 13 | 5.54 | 2.00 | 3.11 | 8.71 | 0.71 | 0.47 | 1.20* | 0.813 | 0.77 | 0.864 |
| Other Conifers | 74 | 2.93 | 1.14 | 1.13 | 5.52 | 0.45 | 0.36 | 0.61 | 0.845 | 0.52 | 0.800 |
| Sugar maple | 203 | 6.51 | 2.04 | 2.47 | 12.05 | 1.38 | 1.07 | 2.93 | 0.619 | 1.23 | 0.635 |
| Red maple | 24 | 4.92 | 1.41 | 2.77 | 7.97 | 1.11 | 0.97 | | | | |
| Yellow birch | 34 | 5.97 | 3.06 | 1.39 | 12.65 | 1.59 | 1.33 | 1.82 | 0.878 | 1.64 | 0.720 |
| White birch | 21 | 4.31 | 1.22 | 3.08 | 7.36 | 0.92 | 0.57 | 1.83 | 0.665 | 0.82 | 0.566 |
| Northern red oak | 3 | 6.46 | 3.68 | 2.39 | 9.54 | 0.74 | 0.48 | Non-significant regression | | | |
| White pine | 10 | 4.86 | 1.73 | 3.11 | 8.71 | 0.72 | 0.50 | 1.24* | 0.791 | 0.80 | 0.812 |
| Balsam fir | 57 | 2.65 | 1.07 | 1.13 | 5.52 | 0.43 | 0.34 | 0.48 | 0.892 | 0.49 | 0.793 |
| White spruce | 6 | 4.57 | 0.53 | 4.00 | 5.48 | 0.37 | 0.34 | Non-significant regression | | | |
| Eastern white cedar | 8 | 3.75 | 0.69 | 2.71 | 4.98 | 0.55 | 0.50 | Non-significant regression | | | |
| **DBH (cm)** | 687 | 21.9 | 13.3 | 2.6 | **83.5** | 5.0 | **5.5** | 5.23 | **0.852** | 6.8 | **0.742** |
| Poplars | 42 | 25.2 | 10.9 | 10.8 | 53.4 | 3.8 | 3.3 | 5.26 | 0.799 | 4.5 | 0.833 |
| Other Hardwoods | 379 | 25.8 | 13.1 | 3.7 | 83.5 | 6.5 | 6.4 | 8.70 | 0.787 | 7.6 | 0.662 |
| Pines | 13 | 29.1 | 15.0 | 9.0 | 51.7 | 3.2 | 2.8 | 3.64 | 0.823 | 2.4 | 0.977 |
| Other Conifers | 253 | 15.1 | 11.0 | 2.6 | 46.0 | 3.0 | 3.3 | 2.20 | 0.871 | 4.2 | 0.852 |
| Sugar maple | 262 | 26.1 | 13.0 | 3.7 | 66.5 | 6.7 | 6.3 | 9.94 | 0.736 | 7.2 | 0.690 |
| Red maple | 31 | 25.3 | 12.5 | 8.9 | 68.0 | 7.4 | 7.7 | -18.62* | 2.000 | 9.5 | 0.445 |
| Yellow birch | 36 | 26.8 | 19.0 | 6.2 | 83.5 | 7.4 | 8.6 | 5.37* | 1.028 | 9.8 | 0.739 |
| White birch | 47 | 23.1 | 7.5 | 10.2 | 37.7 | 3.9 | 3.6 | 8.04 | 0.736 | 4.1 | 0.704 |
| White pine | 10 | 23.5 | 12.1 | 9.0 | 44.7 | 2.3 | 0.9 | 2.92 | 0.859 | 1.6 | 0.984 |
| Balsam fir | 170 | 8.8 | 5.8 | 2.6 | 29.0 | 1.8 | 1.4 | 0.80 | 0.954 | 2.3 | 0.847 |
| White spruce | 10 | 30.9 | 7.3 | 18.7 | 45.3 | 2.8 | 2.1 | 4.05* | 0.899 | 3.5 | 0.791 |
| Eastern white cedar | 73 | 27.6 | 7.0 | 14.5 | 46.0 | 5.7 | 4.8 | 14.83 | 0.460 | 5.4 | 0.414 |

[a] Intercept coefficients marked with * have non-significant p-values (> 0.05); all other coefficients have significant p-values (< 0.05)

[b] All slope coefficients have significant p-values (< 0.05)

[c] Root mean squared error or standard error of the estimate

to discern differences of 0.01 mm. The average observer can discern differences of 0.05 mm and some highly trained interpreters can detect differences in parallax of about 0.03 mm (Johnson 1957), but 5-cm classes at this scale of photography are probably too fine for even very skilled interpreters. Even 10-cm classes require detecting differences of less than 0.03 mm. Using 15-20 cm diameter classes is probably a more realistic and practical standard for measuring downed wood diameter in LSPs of the scale tested in this study (1:433)

In an LSP logging residue study using 1:373 scale photos, LSP estimates of piece counts, lengths, diameters, and volumes were significantly correlated with ground measures (Lyons 1967). The Lyons (1967) study evaluated a larger scale of photography, and likely included larger piece sizes than our study, which should have resulted in higher correlations between the two measurement methods; however diameters were not reported in the paper.

## Classifying tree quality

Photo classification of tree quality was better than anticipated. The interpreter was able to see and evaluate a significant portion of the stem of many larger-diameter trees. The interpreter correctly classified 71 of 96 hardwood trees to two classes, acceptable (AGS) or unacceptable (UGS) growing stock (Table 11). Of 67 trees ground-classified as AGS, 84% were also classified as AGS in the photos. However, photo classification tended to overestimate tree quality. Of the 29 trees ground-classified as UGS, only 48% were classified as UGS in the photos. In tree quality classification, trees are downgraded as defects are observed. With vertical photography, much of the stem is not visible, so even major defects may not be detected during photo interpretation. Stem visibility is further restricted for trees with less (or no) lean, near the photo centre, and that are otherwise obstructed in the photos.

Not surprisingly, classifying tree quality in LSPs using the 6-class system was more difficult and less accurate than what we found using the 2-class system. Only 41% of 96 trees were assigned the same ground and photo class. The bias towards assigning higher tree classes in the photos than from ground evaluation was more pronounced than in the 2-class system. Of 57 other trees, 70% were assigned a higher class by the photo interpreter than by the field crew (Table 11).

Weaker results for the 6-class system and overestimation of tree quality are not surprising because the 6-class system requires more information to distinguish among classes. A skilled ground crew is better able to evaluate trees on all log faces and to correctly detect important but subtle tree degradation characteristics than a photo interpreter. Our study suggests that LSP can provide 2-class (AGS/UGS) tree classification that may be adequate for stand-level characterization of tree quality as part of a forest resource inventory, but is biased, i.e., overestimates quality.

***Table 10.*** *Descriptive and linear regression statistics for ground- and photo-measurements of downed wood length and diameter (butt, top, and average). Linear regressions (ground measurement = f(photo measurement)) were significant ($\alpha < 0.001$) with high statistical power ($1-\beta > 0.8$).*

| Variable | n | Ground measurement Mean | St. Dev. | Min. | Max | Ground photo Mean paired | St. Dev. | Regression equation Intercept[a] | Slope[b] | Regression statistics RMSE[c] | r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Downed wood length (m) | 128 | 4.41 | 3.15 | 0.00 | 4.83 | 0.82 | 0.86 | 0.152* | 1.060 | 1.12 | 0.875 |
| Downed wood diameter (cm) | 32 | 14.43 | 10.7 | 2.9 | 40.6 | 5.5 | 4.5 | 5.08* | 0.702 | 6.4 | 0.581 |
| Butt | 33 | 21.3 | 15.0 | 4.0 | 72.3 | 6.8 | 5.5 | 3.35* | 0.950 | 8.6 | 0.681 |
| Top | 33 | 10.2 | 8.9 | 1.6 | 30.1 | 4.8 | 3.3 | 4.96 | 0.507 | 4.0 | 0.564 |

[a]. Intercept coefficients marked with * have non-significant p-values (> 0.05); all other coefficients have significant p-values (< 0.05)
[b] All slope coefficients have significant p-values (< 0.05)
[c] Root mean squared error, or standard error of the estimate

***Table 11.*** *Ground and photo-classified tree quality for 96 hardwood trees from 36 plots. The frequency of correctly classified trees is given for both the six- and two-level classification schemes. Types of misclassifications are given with their frequencies in parentheses. Only the two-class system is applicable for trees < 10 cm dbh.*

| Ground classification | | | | Photo interpreted classification | | |
|---|---|---|---|---|---|---|
| | | | | | Misclassification type | |
| Tree size | Two-class | Six-class | Total | Correctly classified (No.) | Correct AGS/UGS[c] | Incorrect AGS/UGS[d] |
| > 10 cm DBH | AGS[a] | $A_1$ | 9 | 8 | $B_1$(1) | – |
| | | $B_1$ | 48 | 17 | $A_1$(21) | A(1) B(1) C(5) D(3) |
| | UGS[b] | A | 0 | – | – | – |
| | | B | 14 | 2 | A(2) D(3) | $A_1$(3) $B_1$(4) |
| | | C | 13 | 3 | A(1) B(1) D(2) | $A_1$(3) $B_1$(3) |
| | | D | 0 | – | – | – |
| < 10 cm DBH | AGS | | 10 | 9 | – | UGS(1) |
| | UGS | | 2 | 0 | – | AGS(2) |
| Totals | | | 96 | 39 | 31 | 26 |

[a] AGS = acceptable growing stock
[b] UGS = unacceptable growing stock
[c] Trees > 10 cm dbh correctly classified in 2-class system but misclassified in 6-class system
[d] Trees > 10 cm dbh misclassified in 2-class system and misclassified in 6-class system

## Classifying snag and downed wood decay

Decay classes for snags and downed wood were interpreted for only the 14 old-growth plots. To increase sample sizes for evaluating LSP decay classification, we compared all co-registered snags and downed wood, not just those ≥ 10 cm DBH (snags) or 10 cm largest diameter (downed wood).

Ground- and photo-estimated snag decay classes were similar, and were better than for downed wood (Table 12). Of the 15 co-registered snags, 80% were correctly classified to one of three decay classes. Of 54 downed wood pieces, 63% were correctly classified. Of the 20 misclassified p[illegible] 18 were misclassified by one level, and two were misclassified by two levels.

## Conclusions and Recommendations

Leaf-off imagery produced by this LSP-RMAP™ system may be well suited to augmenting smaller-scale imagery and field sampling for multi-resource forest inventories of mixed and hardwood forests, such as those of the Great Lakes-St. Lawrence region. The suitability of LSP will depend on study objectives. Practitioners will have to determine if the variables of interest can be measured with sufficient accuracy for their purposes. We have presented results for a range of traditional and non-traditional plot variables from one test of this system. Study results are likely to vary, however, with weather (i.e., flying and photographic conditions), terrain, allowable targeting accuracy (i.e., targeting bubble), forest type, and tree phenology.

Our study shows that results from RMAP™-assisted and supplemental LSP interpretation by experienced photo interpreters can provide data on a variety of forest plot and tree attributes, most of which are not currently interpreted using medium-scale photography. Errors in photo targeting, feature detection, classification, and measurement may limit LSP utility for some monitoring and research applications, such as permanent growth and yield or research sample plots that require repeated capture of individual plots or higher spatial accuracy of measurements.

As LSP technology is not widespread at this time, standards for quality of photography and photo measurements have not yet been well developed. Those intending to apply this technology should allocate sufficient time with their LSP provider during contract development to ensure agreement on specific mission objectives to maximize the likelihood of receiving the desired products.

***Table 12.*** *Ground and photo assessments of decay class for 15 snags and 54 pieces of downed wood from 14 old-growth plots. The frequency of correctly classified features is given as well as the type and frequency of misclassified features.*

| Type | Decay class[a] | Total | Correctly classified (No.) | Misclassification type |
|---|---|---|---|---|
| Snags | 1 | 10 | 9 | 2(1) |
| | 2 | 3 | 3 | – |
| | 3 | 2 | 0 | 1(1) 2(1) |
| **Snag totals** | | **15** | **12** | **3** |
| Downed wood | 1 | 11 | 4 | 2(7) |
| | 2 | 12 | 10 | 1(1) 3(1) |
| | 3 | 31 | 20 | 1(2) 2(9) |
| **Downed wood totals** | | **54** | **34** | **20** |

[a] Decay class definitions for field and photo interpretation
1 = recently dead, bark mostly on, most branches still attached, most of tree height intact
2 = partly decomposed, branches and bark off (bare logs, stubs), tree height 50-75% of original
3 = decomposition evident, moss encroaching on log and various levels of incorporation of material into forest floor, standing material reduced to broken stubs, stumps and hollow, <50% of original height

We provide the following additional recommendations for LSP for forest plot sampling applications in the Great Lakes-St. Lawrence region of Ontario:

(1) For mixed and hardwood forests, leaf-off photography is essential. Timing photography to capture phenological differences among species, although tricky, will likely aid tree species identification. In closed canopy deciduous forest stands, leaf-on photography is not generally suitable due to problems with altitude measurement and thus photo scale and all scale-dependent measurements. Leaf-on photography also precludes measurement of most subcanopy features.

(2) With a prescribed allowable target error of 5 m, expect actual targeting accuracies in the range of 2 to 22 m, in similar forests and under similar conditions. If a larger target error is permissible, large-scale photography using this system should require less aircraft time to correctly position the camera over a target, and therefore less expense.

(3) Establishing the centre of the photo plot at the stereo centre of the images provides the best stereo coverage of an area. If the front or rear principal point is to be chosen for ease of interpretation, and a pre-defined location is photographed, the rear principal point is closer, on average, to the location and is therefore the better choice for plot centre.

(4) When we tested the system, RMAP™ input data could not be edited in the event of an interpreter input error, such as incorrect selection of species when a tree record is created. If an interpreter noticed an error and wished to correct one or more records (trees), the entire plot had to be reinterpreted. We have recommended that the necessary programming changes be made to RMAP™ to correct this limitation.[1]

(5) Trees sampled to estimate regression equations should be restricted to the distribution(s) of tree sizes that will be detected on photos, and to similar sites. If only codominant and dominant trees will be detected, regression equations based on trees of these sizes should yield better relationships between ground and photo measures. For some overstory species that also occupy gaps (e.g., balsam fir), separate equations for different size classes would likely improve relationships.

(6) Modifying RMAP™ to permit entry of additional model forms for regression equations would ensure that the most appropriate equation is used for each species.[1]

[1] Improvements have been made to RMAP™ since we conducted our tests. Contact R&B Cormier, Inc., Sault Ste. Marie, ON for details.

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